Intense linear ion accelerators

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Usp. Fiz. Nauk 132, 639–661 (December 1980)

Intense linear ion accelerators are playing an ever more important role in the program of seeking new energy sources. The fundamental physical effects that limit the beam current and technical problems associated with these effects are discussed. The prospects for building intense linear accelerators for energetics and possible parameters of these machines are discussed.

PACS numbers: 29.15.Dt

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1. INTRODUCTION

The first modern linear proton accelerator was built in 1946.[1] Since that time, during more than thirty years, linear ion accelerators have served only as devices for high-energy physics. In the overwhelming majority of cases, they have been used as injectors for proton synchrotrons. Currently, the important role of linear ion accelerators in the program of seeking new energy sources is becoming ever more obvious.[7-11]

The extensive program of development of thermonuclear energetics includes studies on radiation materials science associated with the development of construction materials for the primary wall of thermonuclear reactors. An apparatus designed for testing various samples of construction materials must achieve a high flux density of neutrons of energy in the 14-MeV region. A neutron generator is needed with a flux up to 10^{15} neutrons/cm^2 in a volume of the order of 10 cm^3.[2,3] The need for such a neutron generator will continue to grow, since the successful starting of a demonstration reactor will give a strong boost to the development of the entire field of thermonuclear energetics. Yet the thermonuclear reactors themselves cannot ensure a reasonable tempo of the materials-science studies. A high-flux neutron generator will also make possible the study processes of accumulation of fission products in absorbers made of uranium or thorium, which have been proposed as shielding for thermonuclear reactors. The only possibility currently known for building high-flux neutron generators of 14-MeV energy is a combination of a 35-MeV deuteron accelerator having a continuous beam current of 100–200 mA and a transmission lithium target.[4-6]

The prospects of employing intense accelerators for solving problems of energetics, as well as for a number of other fields of technology, have heightened the interest in these machines. A considerably better understanding of the physical problems involved in building intense accelerators has been gained in recent years. Both cyclic and linear accelerators have been examined. However, experience in design has made it every more convincing that linear accelerators (linacs) are preferable to cyclic accelerators for obtaining ion beams with a mean current larger than 1–10 mA. The pertinent arguments will be discussed below.

In line with the expansion of the fields of application of linear ion accelerators (ion linacs), the meaning of the term "intense linac" has changed in time. Table I gives the data on linacs that are characteristic of intense machines in different periods. The injectors of proton synchrotrons (PSs) operate in a pulsed regime with a large off-time; these accelerators were termed intense if they yielded beams with a large pulse current, independently of the value of the mean beam current. However, now the term "intense linac" refers only to a linac having a large beam current. Intense linacs of the next generation (meson factories) yield proton beams with a mean current up to 1 mA.[12,13] The projected intense Linacs of the third generation are designed for producing continuous beams with a current of several hundred milliamperes.[4-6,8,14,15]

We should also include in the third-generation accelerators the pulsed Linacs for heavy ions of small

 0038-5670/80/120835-13$01.10

TABLE I.

Name	Scientific center	Starting year	Year of reaching maximum current	Pulse beam current, mA	Mean beam current, mA
Injector for proton synchrotron (PS)	CERN	1959	1971	140	0.028
PS injector	ITÉF (USSR)	1966	1972	200	0.002
PS injector	Batavia (USA)	1971	1977	300	0.01
Meson factory	Los Alamos (USA)	1972	1977	16	1
Meson factory	MRTI, IYaIAN (USSR)	In construction		50 (projected)	0.5 (projected)
Neutron generator	ITEF (USSR) Los Alamos (USA)	Projected		—	100—200
Installation for producing nuclear fuel	Brookhaven (USA) Chalk River (Canada)	Projected		—	300

charge (up to U^{2+}), which in the future may find an important application in thermonuclear energy installations employing inertial fusion reaction.[16-18] These accelerators are designed for producing ion beams having a large pulse current with a relatively low off-time. The mean beam current can reach 10 mA or more. A number of problems involved in the construction of intense heavy-ion Linacs pertain also to proton machines, but the heavy-ion Linacs also have their own specific difficulties. We shall be dealing below only with intense linear accelerators for protons or deuterons.

The next section will briefly treat the fundamental physical effects that limit the beam current in a Linac. We present some results of the theory that determine the limiting values of the pulse current and the mean current. Ultimately, the technical difficulties of building third-generator intense Linacs stem from these physical effects, and are very serious. In the subsequent sections we analyze the technical problems and substantiate the choice according to current views of rational ways of building intense Linacs. For the entrance section of intense Linacs, the most advantageous accelerating structure proves to be one with spatially uniform quadrupole focusing. A separate section is devoted to this structure. Due to the limited scope of this review, we shall not present information on the theory and technology of Linacs, which have been discussed extensively in various monographs. However, we cite the necessary literature references that can be utilized by interested readers who are not specialists in accelerator technology.

2. EFFECTS THAT LIMIT THE BEAM CURRENT

The limiting ion-beam current of a Linac is restricted by a number of factors. The major ones are: the finite size of the phase volume of the beam at the entrance of the accelerator; the repulsive forces of the self-field of the beam; and the effect of expansion of the phase volume during acceleration. There are also a number of other limiting effects, e.g., scattering of the particles by the residual gas, binary collisions in the beam, and external and parametric resonances. However, the latter effects play no substantial role in the process of accelerating beams in a Linac. As a rule, we can neglect them.

Various focusing systems are employed for confining the particles in the region of interaction of the beam with the accelerating field. Usually alternating-gradient focusing is applied. Confinement of particles by a longitudinal magnetic field has not been widely applied, owing to the requirement of very high power in the focusing field, and also because inadmissibly large ponderomotive forces arise between the coils of the solenoids. Compensation of the space charge of the ion beam in a Linac with an electron beam cannot be employed, since the electrons are defocused in the alternating-gradient field that focuses the ions. All the ion Linacs of energies up to 100–200 MeV that have been put into operation up to now have been based on an Alvarez accelerating structure with alternating-gradient quadrupole focusing, as proposed for the Linac by Blewett.[19] The Alvarez-Blewett structure has been described in detail in the literature.[20,21] This structure amounts to a cylindrical resonator loaded with drift tubes. An E_{010}-type standing wave is excited in the resonator. Quasistatic quadrupole focusing is applied in the accelerating systems employing drift tubes. To do this, electromagnetic quadrupoles are installed in the tubes. Currently a number of scientific centers are studying the highly promising possibility of operating with magnetically hard quadrupoles.[22-25]

In recent years accelerating and focusing systems differing from the Alvarez-Blewett structure have been studied intensively. In these, the alternating-gradient focusing is achieved using a high-frequency accelerating field ("horned" electrodes,[26,27] spatially uniform quadrupole focusing,[28] alternating-phase focusing[29,30]).

Let us examine the effects that limit the ion current in a Linac.

a) The finite phase volume of the beam at injection

A beam is said to be matched if the initial conditions of the beam at the entrance of the Linac are such that the envelope of the beam is constant or is a periodic function over the course of the focusing channel. Matched beams correspond to optimal focusing. If the space-charge density is negligibly small, then the maximal dimensions of a matched beam in a given focusing channel are determined only by its phase volume. One usually takes the measure of the phase volume of a beam to be a quantity proportional to the area of the projection of the six-dimensional volume on each of the transverse phase planes, e.g., $x, p_x/m_0c$:

$$V_b = \frac{1}{\pi m_0 c} \int dx\, dp_x. \tag{1}$$

This quantity is called the normalized emittance of the beam, and it does not depend on the energy of the particles. In the simplest case in which the focusing forces are linear, the emittance of a beam matched with its focusing channel is enclosed in an ellipse. Here the normalized emittance equals the product of the semi-axes of the ellipse in the displacement vs reduced momentum plane:

$$V_b = \frac{\gamma}{c}\omega_r R^2. \quad (2)$$

Here R is the present radius of the envelope, and ω_r is the present frequency of the transverse oscillations. In the general case, the emittance of the beam is enclosed by a boundary curve differing from an ellipse. Then the normalized emittance is defined as the area occupied by the representative points of the beam in the displacement vs reduced momentum plane divided by π. Henceforth we shall omit the coefficient π in the value of the normalized emittance.

In a channel with alternating-gradient focusing, the frequency of the transverse oscillations is a periodic function having the period of the focusing structure. The maximum possible value of the normalized emittance of a beam passing without losses through a given channel is called the admittance of the channel or its normalized acceptance:

$$V_c = \frac{\gamma}{c}\omega_{r,m}a^2. \quad (3)$$

Here a is the radius of the aperture, and $\omega_{r,M}$ is the minimum instantaneous frequency of the transverse oscillations, as determined by the alternating-gradient focusing forces. A beam will pass through a Linac channel without losses if the condition $V_b \leq V_c$ is satisfied. Since the admittance of a Linac channel has an upper bound determined by technical possibilities, while the phase volume of the beam at a given current has a lower bound, the latter condition proves to be the most important factor limiting the intensity of the beam.

b) The effect of the self-field of the beam

Due to the effect of autophasing, a beam in a high-frequency accelerating field breaks down into bunches. The maximal instantaneous current in a bunch is called the peak current J_{peak} of the bunch. The mean beam current J is related to the peak current of a bunch by the relationship

$$J = BJ_{peak}.$$

Here B is by definition the bunching coefficient, which mainly depends on the equilibrium phase and the tempo of acceleration. If the accelerator operates in a pulsed regime, then J is the current averaged over a pulse. The total charge of a bunch can be expressed in terms of the peak current of the bunch for a given charge distribution. Thus the peak current governs the effects associated with the self-field of the beam. In the general case, the bunching coefficient depends on the peak current of a bunch. However, this dependence is relatively weak.[31]

The ratio of the peak current of a bunch to the normalized emittance of the beam is called the phase current density of the beam[31]:

$$j = J_{peak}/V_b.$$

In the general case in which the phase density is not constant, we have the local values of the density $j = dj_{peak}/dV_b$. If j is not very large, then the maximum mean beam current is

$$J_{max} = jV_cB. \quad (4)$$

For a given frequency of the accelerating field, the admittance of a channel cannot vary over a wide range. Therefore, in designing injectors, the main effort in increasing the beam current has been concentrated on increasing the phase density of the beam at the input of the Linac. The simplest of the ways that have been employed has been the method of preliminary bunching of the beam. However, the main problem has involved studying the nonstationary phase distributions between the ion source and the Linac. The experimental work on improving the ion optics of the preinjectors and modernizing the channels between the preinjector and the Linac have made it possible to increase substantially the phase density of the beam at the Linac input. The phase density of unbunched proton beams has been raised from 250–300 mA/cm · mradian in 1966 to 600–700 mA/cm · mradian in 1971–1972. This has made it possible to increase the pulsed current of the beam at the output of the Linac to values of the order of 200 mA. Currently the phase density of unbunched proton beams has reached values of 1–2 A/cm · mradian.

If transverse Coulomb repulsion substantially affects the motion of the particles, then the maximum dimension of a beam in a focusing channel is larger than the quantity

$$R_c^0 = \sqrt{\frac{cV_b}{\gamma\omega_{r,m}}} \quad (5)$$

as defined by its phase volume. In order to estimate the effect of transverse Coulomb repulsion on the dynamics of particles, the self-consistent (in the sense of Vlasov) self-field of the beam has been examined. One can show that the dimensions of the beam in a given focusing channel depend weakly on the form of the distribution function of the phase density. The most convenient distribution has proved to be one analogous to a microcanonical distribution.[79] This phase distribution corresponds to beams with a uniform distribution of space-charge density over any transverse cross-section, and it yields the simplest analytic relationships between the fundamental parameters of the beam and of the channel.[31] Let us introduce the parameter

$$j_0 = \frac{\Omega_r^0}{c}\beta\gamma^2 J_0. \quad (6)$$

It has the dimensionality of the phase density of the beam current. Here Ω_r^0 is the mean frequency of the transverse oscillations of the particles in a beam of negligibly small intensity. J_0 is the characteristic ion-beam current:

$$J_0 = 4\pi\varepsilon_0 \frac{m_0c^3}{e}. \quad (7)$$

The maximum dimension of a matched beam is related as follows to the phase density of the current:

$$R_c = R_c^0\sqrt{h + \sqrt{h^2+1}}. \quad (8)$$

Here we have $h = j/j_0$. The parameter j_0 is the criterion that characterizes the effect of the self-field of the beam on the dynamics of the particles. When $j \ll j_0$, we can neglect the self-field of the beam. When $j \gg j_0$, the dimensions of the beam are mainly determined by the beam current and are practically independent of the phase volume of the beam. The space charge of the beam for given values of the acceptance and of the frequency of the transverse oscillations primarily affects the focusing of particles at low energies, as long as the parameter j_0 is small.

The maximal dimension of the beam in (8) must not exceed the radius of the aperture. Hence we obtain an expression for the limiting admissible mean beam current. For a given emittance of the beam at the input of the Linac, we have

$$J_{\max}=\frac{1}{2}j_0V_cB\left[1-\left(\frac{V_b}{V_c}\right)^2\right]. \quad (9a)$$

If the phase density of the current is given, then the limiting admissible mean beam current is

$$J_{\max}=j_0V_cB\frac{h}{\sqrt{1+h^2}+h}. \quad (9b)$$

The limiting beam current increases monotonically with increasing admittance of the channel and with increasing phase density of the injection current. If the phase density is small ($j\ll j_0$), then the limitation of the beam intensity is determined for a given phase density by the value of the maximum admissible emittance of the beam transmitted by the channel. When $j\ll j_0$, Eq. (9b) gives rise to Eq. (4). The limiting current reaches its maximum when $j\gg j_0$ and asymptotically approaches the following value as $j\to\infty$:

$$J_{\max}^{\infty}=\frac{1}{2}j_0V_cB. \quad (10)$$

The phase density of the current is the most important parameter of the ion sources and of the optics between the source and the Linac. At a proton energy of 700 keV, a linear accelerator at the wavelength $\lambda=2$ m corresponds approximately to $j_0\approx 3$ A/cm · mradian. Since the phase density of the current in proton sources during the initial stage of development of Linacs did not exceed 6–10 mA/cm · mradian, the enhancement of the intensity of the accelerated beam mainly arose from work on perfecting the ion sources. The most promising type of ion source for proton Linacs has proved to be the duoplasmatron, to whose development much attention has been paid. As we have noted above, currently the phase density of the injection current has been raised by two orders of magnitude.

The main way to increase substantially the admittance of a Linac is to increase the wavelength of the accelerating field, which allows one to increase the aperture of the channel. This method is effective if the gradient of the focusing field is limited by the maximum induction of the poles of the magnetic quadrupoles or the dielectric strength of the radiofrequency quadrupoles. In this case one can increase the admittance in proportion to the square of the wavelength of the accelerating field. However, in a continous-action Linac having electromagnetic quadrupoles, the admittance is usually limited by the power dissipation in the lenses, since the latter is proportional to the 4th power of the aperture. Increase in the wavelength proves considerably less effective, although it remains the main way to increase the acceptance.

As the injection energy increases, the maximum possible admittance of magnetic quadrupole channels increases in proportion to the square root of the injection energy. In electric quadrupole channels, the admittance is practically independent of the injection energy. As we can easily see, this feature of the different channels involves the fact that the stiffness of a magnetic channel is determined by the Lorentz force, while the stiffness of an electric channel does not depend on the velocity of the particles. The dependence of the limiting current on the injection energy when $j\ll j_0$ (4) has the same form as the dependence of the admittance. Hence we see that magnetic quadrupole focusing proves unsuitable at low particle velocities. This, in particular, has determined the interest in focusing beams in Linacs with electric forces. One can use as the electric focusing forces the transverse components of the radiofrequency accelerating field if one rules out axial symmetry of the field. Vladimirskiĭ[32] first proposed such an idea. The gradient of the focusing electric field can periodically change sign in space (along the axis of the accelerator) or in time. As the phase density increases, the dependence of the limiting current on the injection energy is strengthened. Since, according to (6), we have $j_0\sim\sqrt{W_{\text{inj}}}$, then in magnetic quadrupole channels we find $J^{\infty}\sim W_{\text{inj}}$, while in a system of electric quadrupoles we have $J^{\infty}\sim\sqrt{W_{\text{inj}}}$. Thus, the injection energy in intense Linacs employing magnetic quadrupoles must be sufficiently high. This defines the difficulty in designing and employing Linacs. The energy of the particles at the input of intense Linac injectors for $\lambda=1.5$–2 m is usually taken to be 700–750 keV.

As one can show, the current limit arising from longitudinal Coulomb repulsion is approximately proportional to the cube of the equilibrium phase. In an accelerator with quadrupole focusing, the absolute value of the equilibrium phase can be made so large that the effect of longitudinal repulsion does not restrict the beam current. Longitudinal repulsion can play an appreciable role in certain radiofrequency focusing systems in which it is difficult to obtain bunches of sufficient duration, e.g., in a system having alternating-phase focusing.

c) The effect of expansion of the phase volume of the beam during acceleration

Thus far we have assumed that the phase volume of the beam in the four-dimensional phase space of the transverse oscillations is bounded. If the conditions of the Liouville theorem are fulfilled, i.e., dissipative forces are absent and the continuity equation holds in phase space, then the four-dimensional phase volume must remain invariant during acceleration. In the absence of coupling between the transverse degrees of freedom, the emittance of the beam in the phase plane must be conserved. However, actually an irreversible increase in the normalized emittance of the beam occurs during the acceleration process. The increase in the emittance leads to losses of particles to the walls of the accelerating system. These losses are hard to avoid, even when a certain safety factor has been provided in the accelerator in the value of the acceptance.

The increase in the normalized emittance in a linac does not contradict the Liouville theorem, since it involves either a breakdown of the condition of continuity of the flux, or irreversible changes in the form of the emittance, which are manifested in practice as an increase in its dimensions. An exaggerated analogy of the latter effect is the winding of a straight-line segment into a helix.

The most substantial increase in the normalized emittance occurs in the low-energy region, and is governed mainly by the coupling between the transverse and longitudinal oscillations of the particles. During the subsequent acceleration process, the increase in the normalized emittance arises mainly from random perturbations of the beam in the focusing channel when the transverse forces are nonlinear. This increase occurs relatively slowly but without limit, so that the beam tends to occupy all the acceptance of the accelerator available to it. In the general case, the tempo of the expansion of the transverse phase volume depends on the design and parameters of the focusing and accelerating systems. Measurements of the Linac beam in various scientific centers show that the increase in the normalized emittance mainly arises from the "halo" of the phase volume; the phase density of the current in the core of the emittance decreases but little. The intensity of the beam has little influence on the effect of expansion of the phase volume. According to the data from CERN, the minimum attainable emittance at the output of the Linac is proportional to the 1/3 or 1/2 power of the beam current.[33] In the experiments of the Institute of Theoretical and Experimental Physics with a pulsed current at the Linac output greater than 100 mA, no dependence of the output emittance on the intensity could be detected.[34] However, in the acceleration of an intense continuous beam, the expansion of the "halo," even when the latter has a a relatively low density, constitutes a great hazard involving the considerable irradiation of the construction materials of the Linac.

No unified theory of the expansion of the phase volume of the beam in a Linac exists as yet. An extensive literature has been devoted to various aspects of the problem.[35-40] A large number of factors exists that influence the effect of expansion of the phase volume of a beam during acceleration. The role of these factors is not the same in individual accelerators. We discuss below some general regularities.

Exact matching of the beam to the focusing channel is possible in principle only in the absence of accelerating fields. In a linac, only the set of equilibrium particles can be matched. For simplicity, let us choose the coordinates of the phase plane in such a way that the trajectories of equilibrium particles in the harmonic approximation are circles. The emittance occupied by the equilibrium particles is a circle in this plane. If the phase trajectories are not distorted in shape, then the circular emittance rotates unchanged. Let us assume that the circular emittance at the input of the Linac includes the representative points of all the nonequilibrium particles of the beam at the input. The nonequilibrium particles move along open phase trajectories with a phase velocity that differs from the phase velocity of rotation of the equilibrium particles. The trajectory of a nonequilibrium particle depends both on the initial values of the transverse variables and on the initial phase of the particle with respect to the radiofrequency field. The phase trajectories of the nonequilibrium particles begin in the common circular area occupied by all the representative points of the beam at the input of the accelerator. However, the maximal distance of many particles from the origin of coordinates exceeds the radius of the original circle, and this considerably increases the phase volume. Figure 1 shows schematically the effect of "smearing" of the emittance of the beam caused by the coupling of the transverse and longitudinal oscillations. The solid circle encloses the phase trajectories of the particles having equilibrium phases. Hence it is the boundary of the emittance of a matched beam at the input of the linac. The representative points of all the nonequilibrium particles subsequently move in various elliptical trajectories that are deformed relatively slowly. The dotted circle encloses all the trajectories of the nonequilibrium particles and is the boundary of the increased emittance of the beam. An increase in emittance of the same type also arises from the coupling between the transverse degrees of freedom caused by nonlinearity of the external fields or nonlinearity of the Coulomb forces. However, the latter effects are substantially weaker. An analytical estimate gives as the first approximation the following expression for the radius of the circle covered by the trajectories of all the nonequilibrium particles[41]:

$$R_1 \approx R_0 \left(1 + \frac{\Phi}{|\tan \varphi_s|} \frac{\Omega^2}{4\Omega_{r,s}^2 - \Omega^2}\right). \tag{11}$$

Here R_0 is the radius of the circle corresponding to the emittance of the beam at the input of the Linac, Φ is the maximal amplitude of the phase oscillations, Ω is the frequency of the phase oscillations, and $\Omega_{r,s}$ is the mean frequency of the transverse oscillations of an equilibrium particle. As we see from Eq. (11), the increase of the phase volume caused by the coupling between the degrees of freedom is bounded. The major "smearing" of the emittance occurs in the entrance section of the Linac, since the amplitude and the frequency of the phase oscillations are damped. The expansion of the normalized emittance becomes more

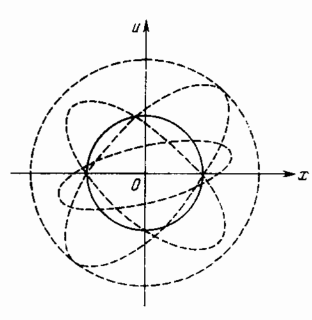

FIG. 1. Phase plane of the transverse oscillations of the nonequilibrium particles.

significant when the particles remain for a longer time near the main parametric resonance band. However, even in cases in which $\Omega_{r,s} \geqslant \Omega$ at the input of the accelerator, the increase in the emittance is very large. We note the estimate by Eq. (11) agrees satisfactorily with the results of machine calculation.[38,42] In the process of further acceleration, the beam remains matched to the channel in the first approximation, but with a correspondingly higher value of the normalized emittance. After this, dematching of the beam by random defects of the channel now plays the major role.

The random defects of the focusing channel lead to stochastic shifts of the emittance from the origin of coordinates and to deviation of its shape from circular. The effective emittance of the beam, i.e., its area in the phase plane within which the representative points of the particles can lie at different instants of time, increases. Correspondingly the amplitudes of the transverse oscillations of the particles increase. However, if the frequencies of the oscillations of all the particles are the same, then the increase in the effective emittance is not accompanied by an increase in the actual phase volume of the beam. Hence it is possible in principle to suppress the increase in the amplitudes of the transverse oscillations by automatic feedback control. However, if frequency dispersion exists, so that $d\mu/dA \neq 0$ (where μ is the phase advance of the transverse oscillations per focusing period, and A is the mean amplitude of the transverse oscillations over the period), then the effective emittance will be smeared out and the actual normalized emittance will correspondingly increase (Fig. 2). The hatched region in Fig. 2 schematically corresponds to the increment in the emittance caused by the frequency dispersion. In the first approximation, coherent perturbations of the beam give rise to an increase in the normalized emittance at the rate

$$\frac{dV_b}{d\tau} \approx \frac{2\gamma}{c}\,\omega_{r,pm} R\,\langle\delta A\rangle^{4/3}\left(\frac{1}{2\pi}\,\frac{d\mu}{dA}\right)^{1/3}. \qquad (12)$$

Here $\langle\delta A\rangle$ is the rms value of the perturbation of the amplitude per period of the focusing structure; τ is the number of periods of the structure. The mean phase density at the periphery of the increasing emittance that is caused by the nonlinear smearing of the area is substantially smaller than in the central region of the emittance. The peripheral density declines with increasing radius. Therefore, just as in the case of

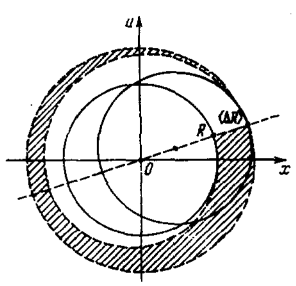

FIG. 2. Diagram of the "smearing," of the effective emittance in the presence of frequency dispersion.

coupling among the degrees of freedom, mainly the halo of the beam grows. However, in this case the growth of the halo of the beam is unbounded.

The frequency dispersion involving the nonuniform distribution of space-charge density over the cross-section of the beam leads to filling of the effective phase volume of the beam with particles in the presence of parametric perturbation. The contribution of this effect is relatively small.

In the Alvarez-Blewett accelerator with $\lambda = 1.5-2$ m, numerical estimates by Eqs. (11) and (12) show that the normalized emittance of a beam matched with respect to the equilibrium particles increases in the first sections of the Linac (0.7–10 MeV) by a factor of about 1.5–2. With the usual assumptions, it subsequently expands at about the rate of 0.01–0.02 cm · mradian/period. The effect of expansion of the phase volume has the result that the actual acceptance of the Linac proves to be substantially smaller than its calculated acceptance. One can diminish the losses by a corresponding decrease in the emittance of the beam. In particular, emittance filters[43] have been proposed for this purpose. In essence they amount to collimators that limit the phase volume. Electronic cooling of the ion beam at the input of the Linac may prove effective.[44] In practice, one can attain a considerable increase in the mean intensity of a Linac beam only when the effect of expansion of the phase volume is suppressed. One can diminish the effect by: decreasing the effect of the phase scatter of the particles on the defocusing of the beam in the accelerating wave; suppressing other possible couplings between the degrees of freedom; ensuring that acceleration starts at high orders of the parametric-resonance bands; further restricting the allowances for random defects and diminishing the coarse local perturbations as much as possible; and improving the linearity of the focusing and accelerating fields.

d) Expenditure of radiofrequency energy in accelerating the beam

The acceleration of the beam requires input of radiofrequency energy, both into the accelerating field and into the beam. In pulsed Linacs, the particles are usually accelerated utilizing the rf energy stored in the field. In order for such a regime to exist the resonators of pulsed Linacs must possess a high quality factor. Thus, the cylindrical resonators with drift tubes excited by an E_{010}-type wave (Alvarez accelerator) have a quality factor of the order of 10^5. During the time of a pulse of the ion current, the field level in the accelerating resonators declines, but its value remains above the threshold level that ensures resonance acceleration. In a number of pulsed Linacs, partial compensation of the expenditures of energy on acceleration has been introduced in order to improve the energy spectrum of the beam or when it is impossible to ensure a high enough quality factor. In accelerators having a constant beam current, a regime of acceleration utilizing the energy stored in the field is impossible in principle; the rf energy spent in accelerating the beam and in compensating the active losses must be supplied to the resonators continuously. The quality factor of the resonators in a continuous-action machine plays no substantial role. The fundamental energy characteristic of the accelerating system of a continuous-action Linac is solely the shunt impedance, which determines the dependence of the active losses of rf power per unit length on the mean field in the resonator. The continuous consumption of energy in intense Linacs requires the construction of an rf supply system with a high mean power. Thus, a linac with a beam energy of 1 GeV and a current of 300 mA will consume about 500 MW of continuous power. This poses very sharply the problems of utilizing high powers in a Linac.

3. TECHNICAL PROBLEMS OF BUILDING INTENSE LINEAR ACCELERATORS

In the plans of most of the installations that require intense ion beams with a mean current of 100–300 mA, building of linear accelerators has been proposed.[4-6,8,9,15,45-47] The physical effects discussed above lead to a number of very difficult technical problems. We can classify these problems into three groups.

The first group of problems includes the building of electrostatic injectors that can produce in the linac a beam of the required intensity.

The second group of problems involves the radiators stability of the materials of the accelerator, the lifetime of the accelerator, and problems of its maintenance.

The third group includes the input into the accelerating system of a large mean rf power and the organization of the cooling.

Similar problems also arise in intense cyclic accelerators. In linear accelerators the latter two groups of problems are solved relatively more simply, since in a Linac one can create a distributed input of the rf power spent in accelerating the beam. The active losses of rf power in the copper can be distributed over a large area, which permits one to lower the specific heat dissipation. The density of the radiation associated with the induced radioactivity is substantially diminished. The usual defect of a linac, which is the considerable cost of the construction and operation of the system of rf supply, is felt less for continuous intense beams, since the power of the rf system of a continuous accelerator is mainly determined by the expenditures in accelerating the beam, rather than by the losses in the copper.

Currently much attention is being paid to the development of continuous-action ion sources. Experience has already been amassed on the design of sources of protons and deuterons with currents of 150–200 mA.[48-50] Although measurements of the emittance of a continuous intense beam present great difficulties, the literature data allow us to draw the preliminary conclusion that one can generate at the input of a linac a beam with a normalized emittance of about 0.2 cm · radian with a phase density of the current of the order of 1 A/cm · mradian. However, in connection with the high injection energies (up to 750 keV) and large currents, complex problems, as yet unsolved, arise of achieving a sufficient dielectric strength of the electrostatic tubes that accelerate the continuous beam.[51] Apparently the cause of the loss of dielectric strength is as follows[52]: the particle beam ionizes the atoms of the residual gas in the electrostatic tube; the free electrons are accelerated in the direction opposite to the motion of the ions, and they generate intense x-rays. Owing to the external photoeffect, the latter give rise to charging and to very large potential drops across the ceramic surface of the tube. In an electrostatic injector, a difficulty also arises that involves the need to supply a considerable constant power to the devices that are kept at high potential. A promising way to overcome these difficulties is the development of radiofrequency accelerating systems, which would enable one substantially to lower the injection energy and current while maintaining the high limiting value of the beam current in the Linac.

The accumulation of scattered particles in the halo of the beam induces radioactivity in the accelerator. Measurements of the induced gamma activity in the vicinity of a number of proton Linacs have allowed an estimate of the index characterizing the losses of particles per unit path[53,54]:

$$n=\frac{1}{J}\frac{dJ}{dl}\approx 10^{-4}-10^{-5}\ \mathrm{m}^{-1}.$$

For a continuous beam current of 100 mA and an index $n=10^{-5}$, the losses per unit path length attain the values $dJ/dl\approx 1\ \mu\mathrm{A/m}$. Problems of the radiation purity of intense linacs have been studied in connection with the design of an accelerator for a meson factory.[43] As is proposed, periodic short-time maintenance of the accelerator by personnel is permissible when the level of induced radioactivity near the accelerator is no more than 50 mr/hr. For a proton accelerator having a particle energy of 30 MeV, this corresponds approximately to losses per unit path of 50 nA/m. For an accelerator with a particle energy of 1 GeV, the losses per unit path should not exceed 0.5 nA/m. At a mean beam current of 100 mA, these values correspond to a loss index $n\approx 5\times 10^{-7}-5\times 10^{-9}\ \mathrm{m}^{-1}$. Apparently such values of the loss index are currently unattainable for actual values of the acceptance of the linac. Therefore linear accelerators with a continuous beam current of 100 mA or higher require construction of a remote-manipulation system.

In order to estimate the lifetime of the accelerator, let us examine a deuteron linac of energy 30 MeV and current 100 mA. The density of the equivalent neutron flux in the inner walls of the accelerator with the stipulated beam parameters amounts approximately to $\nu\approx 10^{18}$ neutrons/(cm^2 · yr · μA/m).[55] We can take the limiting admissible integral flux for copper fixtures to be $N_{tot}=10^{20}$ neutrons/cm^2.[58] Hence we get the following estimate of the lifetime of the drift tubes:

$$\Delta t=\frac{N_{tot}}{\nu\,(dJ/dl)}\sim 100\ \text{years}.$$

Since the values of N_{tot} and ν are crude, it is desirable to anticipate in the design the possible remote replacement of the drift tubes or replacement of the successive collimators that limit the halo of the emittance. A modular design of the accelerating structure is proposed that facilitates replacement of groups of drift tubes.[57]

What are the ways to simplify the problems involved in the realization of intense Linacs? Let us examine some possible schemes of Linacs up to an energy of 30 MeV. The fundamental difficulties lie in this range, even for higher-energy accelerators, since the focusing becomes simpler with increasing energy of the particles, the effect of the self-field of the beam diminishes, and the rate of expansion of the normalized emittance declines.

Currently a number of accelerating and focusing systems exists for the sections at energies below 100–150 MeV. Each of these has its own most suitable region of application. The employment in the main part of the Linac of any particular type of radiofrequency focusing would offer great advantages involving the absence in the drift tubes of electromagnetic quadrupole lenses. In a linac with radiofrequency focusing, it is convenient to employ resonators of small dimensions that can be excited by a longitudinal magnetic wave. However, accelerating structures with rf focusing require a relatively fast tempo of acceleration. Estimates show that currently the best type of intense linear accelerator continues to be the Alvarez accelerator, in which the sources of the accelerating and focusing forces are separate. In such an accelerator one can separately optimize the acceleration and focusing regimes. This is especially valuable for accelerators with a continuous, intense beam. In particular, the possibility of decreasing the tempo of acceleration without impairing the focusing enables one to decrease the total active losses of rf power and to simplify the cooling substantially. This is because, if other conditions remain the same, the total losses are proportional to the tempo of acceleration, while the losses of rf power per unit length are proportional to the square of the tempo of acceleration.

We note that the cost of the accelerating system of a Linac amounts to about 25% of the total cost of the accelerator, including (besides the accelerating system itself) the building and the technical service equipment (rf supply, electrical supply, electronics systems, vacuum units, etc.). Since the cost of an intense accelerator and the cost of the target that interacts with the accelerated beam are about the same, the fractional cost of the accelerating system turns out to be 10–12% of the cost of the entire installation. Thus, the cost of the accelerating system is not the decisive factor in the choice of the structural scheme of the accelerator. The operating reliability of the installation is considerably more important. At present, it is precisely the Alvarez system that is better in this regard, since it has been repeatedly studied and refined in a large number of working pulsed Linacs.

However, the Alvarez accelerator in its classical form possesses substantial defects. The problem of increasing the cooling area and attaining high enough acceptance values have led in the designs completely based on the Alvarez structure[5,46] to choosing a wavelength of the accelerating field of 5–6 m instead of the wavelengths 1.5–2 m commonly employed in pulsed Linacs. This requires the building of unwieldy resonators 3.5–4 m in diameter and drift tubes of diameters up to 70 cm. In order to allow the necessary charged-particle currents, most of the designs have adopted an injection energy of about 700 keV. In producing intense continuous beams, the stated injection energy causes the great technical difficulties noted above. The relatively low capture coefficient complicates the system for preliminary bunching of the beam. A serious problem is the radiation deterioration of the insulation in the electromagnetic quadrupole lenses, since the limiting integral neutron flux in the widely employed insulation materials is four orders of magnitude smaller than in pure metals and alloys. The accelerator of a meson factory employs mineral insulation instead of epoxy resins and fabrics, in particular magnesium oxide.[58] However, the problem of the possible employment of mineral insulation in continuous-beam intense Linacs apparently still remains open.

The problems of building intense Linacs can be simplified to a considerable extent by installing a section with spatially uniform quadrupole focusing between the electrostatic injector and the main part of the accelerator, which amounts to an Alvarez system. We treat a scheme below in which the section with spatially uniform quadrupole focusing is excited by an accelerating field at a frequency half that of the subsequent Alvarez resonators. It is preferable to carry out the quadrupole focusing in the main part of the accelerator with magnetically hard lenses. A variant is possible that employs electromagnetic lenses, provided that insulation materials are found that have the need radiation stability.

4. AN ACCELERATING SYSTEM WITH SPATIALLY UNIFORM QUADRUPOLE FOCUSING

Spatially uniform quadrupole focusing was first described in Refs. 28 and 59. Currently accelerators with spatially uniform focusing are being developed in a number of scientific centers of the USSR and the USA.[60-67]

The fundamental element of the accelerator is the four-conductor radiofrequency line, which creates a quadrupole potential distribution in the region near the axis (Fig. 3). Since an ac voltage is applied to the electrodes of the line, the particles in their motion along the axis successively experience the action of transverse fields with gradients of alternating sign. This gives rise to the effect of quadrupole focusing. A longitudinal accelerating component of the electric field arises in a four-conductor line if the distance between the opposite electrodes of one polarity periodically varies along the axis. The spatial period of variation of the distance between the electrodes must equal the path traveled by an equilibrium particle in a radiofrequency period, while the phases of the variation of the distance in the perpendicular planes are shifted

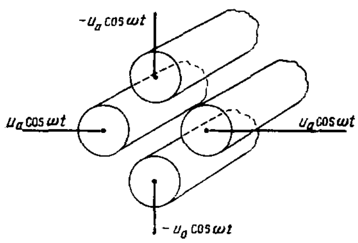

FIG. 3. Four-conductor line with quadrupole symmetry.

by half a period. Here a resonance accelerating effect arises.

In the general case the potential distribution in the paraxial region has the form

$$U(r, \psi, z, t) = [A_0 r^2 \cos 2\psi + A_{01} I_0(kr) \sin kz + \ldots] \cos(\omega t + \varphi). \quad (13)$$

Here we have $k = 2\pi/\beta\lambda$, and ω is the frequency of the accelerating field. Only the fundamental terms that govern the effects of focusing and acceleration have been given in Eq. (13). The rest of the terms of the series in (13) involve side effects, in particular, various nonlinear effects. The sum of the first two terms of the series of (13) corresponds to an ideal field, which can be obtained in principle if the surface of the electrodes coincides with the corresponding equipotentials of this field.[28] In each period $L = \beta\lambda/2$ of acceleration, the particles receive an energy increment

$$\Delta W = eU_L T \cos \varphi. \quad (14)$$

Here U_L is the amplitude potential difference between adjacent electrodes; φ is the phase of the rf field at the instant of time when the particle lies in a cross-section possessing exact quadrupole symmetry; and T is the time-of-flight coefficient, which determines the efficiency of acceleration. In an ideal field we have[28]

$$T = \frac{\pi}{4} \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)}. \quad (15)$$

Here m is the ratio of the maximum distance of an electrode from the axis to the minimum distance; a is the minimum distance of an electrode from the axis. The transverse oscillations of the particles in an ideal field in the case of small partial increments of energy of (14) are described by an equation with an alternating-sign periodic coefficient[64]

$$\frac{d^2 x}{dt^2} - \left(\frac{\omega}{\pi}\right)^2 \left(K^2 \cos \omega t + \frac{1}{2} \gamma_0\right) x = 0. \quad (16)$$

Here γ_0 is the defocusing factor of the particles in the accelerating field,[31,68] which is given by

$$\gamma_0 = -\frac{\pi e U_L T}{2 W_s} \sin \varphi,$$

W_s is the present value of the energy of an equilibrium particle; K is the stiffness of the focusing:

$$K^2 = \varkappa \frac{eU_L}{\mathscr{E}_0} \left(\frac{\lambda}{2a}\right)^2.$$

We define $\mathscr{E}_0$ as the rest mass of a particle; $\varkappa$ is the efficiency of focusing in the modulated four-conductor line:

$$\varkappa = 1 - \frac{4T}{\pi} I_0(ka). \quad (17)$$

The potential distribution in an actual four-conductor line can be determined by numerical methods. Equations (15) and (17) give a quite satisfactory approximation to the time-of-flight coefficient and the efficiency of focusing for electrodes of relatively simple and convenient shape. This shape corresponds in each cross-section to a strip of width $2R_e$ bounded by a semicircle having the radius R_e constant throughout the length (Fig. 4). The distances of the electrodes from the axis vary according to the sinusoidal functions

$$x = R_0\left(1 + \frac{m-1}{m+1} \sin kz\right), \quad y = R_0\left(1 - \frac{m-1}{m+1} \sin kz\right). \quad (18)$$

Here we have $R_0 \approx R_e$.

In the case of (18), the aperture of the four-conductor line, which is

$$a = \frac{2}{m+1} R_0,$$

limits the admittance of the channel given by (3). The minimal instantaneous frequency of the transverse oscillations is determined by Eq. (16). In a "smooth" approximation,[31] we have

$$\omega_{r.m} = \frac{\omega}{\pi\sqrt{2}} \left(1 + \frac{K^2}{\pi^2}\right)^{-2} \sqrt{\left(\frac{K^2}{\pi^2}\right)^2 - \gamma_0}. \quad (19)$$

In a system with spatially uniform quadrupole focusing, the spatial modulation of the envelope of the beam characteristic of a periodic structure involving quadrupole lenses is absent. The beam undergoes pulsations in time that are constant throughout the length.[61] In the general case, the matching of such a beam with the spatially periodic focusing structure requires special radiofrequency apparatus. However, the adiabatic compression of the bunches during acceleration[31,68] enables one to use the ordinary static matching, since the phase spread of the bunches at the input of the Alvarez resonator is already small enough.

Power can be supplied to the four-conductor line in a resonator with a longitudinal magnetic field. Figure 5 shows various types of resonators with a quadrupole wave mode: a double H resonator (Fig. 5a) and two types of four-chamber resonators—a sector resonator[28,64] (Fig. 5b) and a cloverleaf-type resonator[65] (Fig. 5c). Figure 5 shows the direction of the electric field in the paraxial region and of the magnetic field in the resonating volumes. Figure 6 shows a photograph

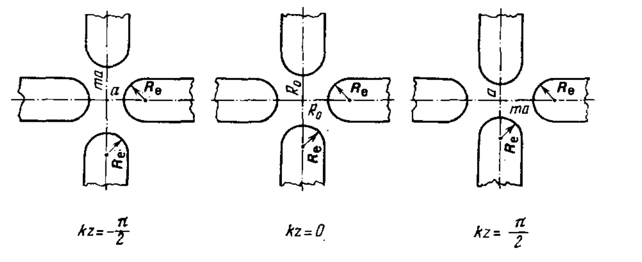

FIG. 4. Cross-sections of the modulated electrodes in an accelerating structure having spatially uniform quadrupole focusing.

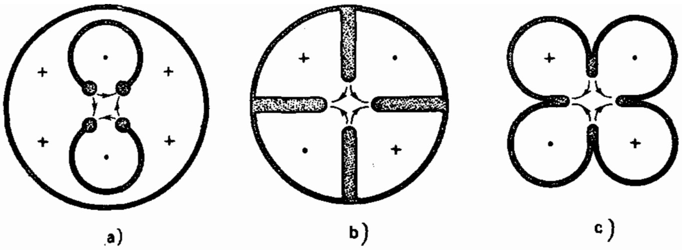

FIG. 5. Cross-sections of volume resonators for accelerating structures with spatially uniform focusing. A longitudinal magnetic wave is excited in the resonators. a) Double H-resonator; b), c) different types of four-chamber resonators.

of one section of an accelerator with spatially uniform focusing.

The design of the accelerating system practically does not limit the possible shortening of the length of the acceleration period. The acceleration in the rf field can be started at a very low injection energy. In spite of the fact that the focusing is performed with a radiofrequency quadrupole field, the stiffness of the focusing in a spatially uniform system does not depend on the phase of the particle with respect to the rf field. Therefore the system allows one to select the equilibrium phase within a broad range. At the input of the accelerator, the equilibrium phase is $-90°$. The bunches follow closely one after another, and the mean current of the captured particles is close to the peak value. In the relatively short initial bunching region, the equilibrium phase is gradually increased by 5–10 degrees. Here the energy of the particles increases somewhat, and the length of the bunches shortens. Now, let us assume that the time-of-flight coefficient T and the equilibrium phase φ_s vary adiabatically along the accelerator axis according to the equations[59]

$$\Phi_s(\varphi_s) = \Phi_s(\varphi_{sf}) \sqrt{\frac{W_{sf}}{W_s}}, \quad T = T(W_{sf}) \sqrt{\frac{W_s \sin \varphi_{sf}}{W_{sf} \sin \varphi_s}}. \qquad (20)$$

Here the index f pertains to the values of the parameters at the end of the initial bunching region, and φ_s is the phase width of the separatrix,[31,68] which is related to the equilibrium phase by the relation

$$\tan \varphi_s = -\frac{\Phi_c - \sin \Phi_s}{1 - \cos \Phi_s}.$$

Then as the energy W_s of an equilibrium particle increases the bunches move apart but maintain invariant geometric dimensions. Since the focusing is carried out with an electric field, the stiffness of focusing for low-energy particles suffices. For a given aperture of the channel, the limiting peak current is four times larger than in the Alvarez system, since the focusing period is twice as short and the admittance is correspondingly higher. The mean beam current along the axis of the accelerator remains constant, so that the maximal mean current proves substantially larger than in the Alvarez system, in spite of the low injection energy. Above a certain value of W_s, the adiabatic variation of T and φ_s must be stopped in order to avoid a decrease in the limiting current involving longitudinal repulsion. The studied bunching process in the entrance section of the accelerator enables one to attain a high capture coefficient without increasing the phase density of the current in the transverse phase volume.

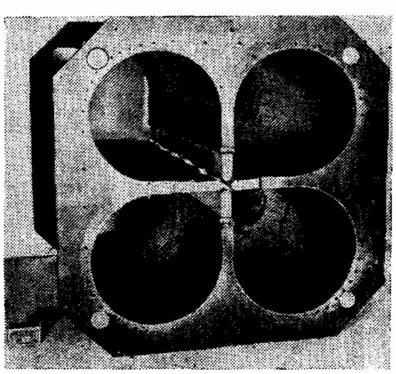

FIG. 6. Section of an accelerator with spatially uniform quadrupole fucusing.

One can carry out the matching of the beam in the transverse coordinates in the entrance section by adiabatic increase in the focusing forces from a low value at the input to the maximal value at the end of the section. The variation in stiffness in the entrance section is carried out by gradual decrease in the mean distance from the electrodes to the axis.[70]

The low injection energy (70–100 keV) and the high capture coefficient (up to 99%) simplify the problem of designing the electrostatic injector. The short acceleration path in the injector allows one to preserve the low value of the emittance of the beam at the Linac input. A largeenough beam current in an accelerator with spatially uniform focusing can be obtained at $\lambda = 4$–6 m. In the main section of the Linac, the beam is introduced at a high energy of the order of 3 MeV.

5. THE STRUCTURE OF THE MAIN SECTION OF AN INTENSE LINEAR ACCELERATOR

The main section of an intense accelerator for proton or deuteron energies up to 100–150 MeV is expediently built in the form of Alvarez resonators. Currently, the optimal accelerating structure for the sections of proton and deuteron Linacs at energies above 100–150 MeV is the system with conducting disks and diaphragms proposed by Andreev.[71,72] We note that, in the range of relative velocities $\beta > 0.5$–0.6, accelerating structures in the form of a chain of coupled single-gap resonators have the highest shunt impedance. In the Linac of the Los Alamos meson factory, a structure has been employed with side-coupling cells.[72,73] The chain of Andreev has a broader dispersion characteristic, and correspondingly it allows an increased stability of the accelerating-field distribution.

At an injection energy of 3 MeV, the admittance of the Alvarez accelerator makes it possible to maintain the required limiting value of the beam current, already at a wavelength one-half that of the section with spatially uniform focusing. The recapture of particles into the acceleration regime can be carried out without losses. Since static focusing is carried out in the main section of the accelerator, the mean accelerating field can be chosen to be relatively small. The low tempo of acceleration correspondingly leads to relatively small active losses of rf power. The specific heat dissipation is considerably diminished, in spite of the short wavelength of the accelerating field. Actually, with other conditions remaining the same, the total active losses of rf power are inversely proportional to the square of the length of the Linac. The specific losses in the walls of the resonators can be reduced to 6 kW/m^2. Increase in the length of the rf structure of the Linac substantially simplifies the solution of the problem of supplying the rf power spent in accelerating the beam. The reduced tempo of acceleration and the shortened wavelength of the rf field also enable one to decrease the coupling between the transverse and longitudinal oscillations, since this coupling is governed by the energy increment of the particles per wavelength.

Installation in the drift tubes of magnetically hard quadrupoles in place of the ordinarily employed electromagnetic lenses simplifies the focusing system of the Linac by solving a number of problems that have initiated the development of rf focusing systems. These problems include: simplification of the very complicated design of the drift tubes, elimination of the stable power supply system, and for intense Linacs, the provision for a sufficient lifetime of the machine. Studies of the possibilities of using permanent magnets in focusing systems in linacs were begun in 1975 and are being performed on a broad front.[24,25,74-76] Modern magnetically hard alloys enable one to build quadrupole lenses that make possible the needed admittance of the focusing channel. The magnetomotive force produced by the alloy depends on the value of the magnetic energy that can be stored per unit volume of the alloy. The alloy YuNDK-35T5 accumulates a specific energy $(BH)_{max} \approx 9$ MG · Oe. With an outer diameter of the lens of 15 cm and a diameter of the aperture of 2 cm, this makes possible a field with a gradient of 6 kG/cm. One can obtain even better results with permanent magnets based on the rare-earth elements. Magnets made of a samarium-cobalt alloy allow one to accumulate a specific energy up to 18 MG · Oe.[77] Rod lenses with nonlocalized poles made of samarium-cobalt alloy not only produce high values of the gradient with small outer dimensions, but also allow a smooth regulation of the gradient.[74] A lens with a regulable gradient consists of several concentric circular rows containing rods made of the alloy $SmCo_5$

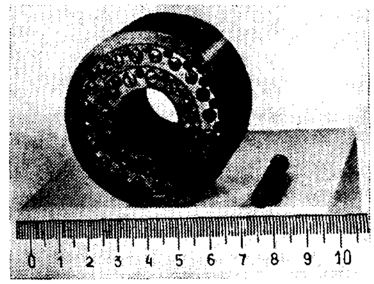

FIG. 7. Magnetically hard quadrupole lens with nonlocalized poles. At the side is shown an individual rod made of a samarium-cobalt alloy.

(photograph in Fig. 7). The rods are magnetized perpendicular to the longitudinal axis. The orientation of the magnetization vectors give rise to a quadrupole field in the aperture. The maximum gradient at the axis of the lens in a first approximation can be estimated by the formula

$$G_{max} \approx 4\pi^2 I \left(\frac{1}{d_a} - \frac{1}{d_l}\right);$$

Here d_a is the diameter of the magnet aperture, d_l is the outer diameter of the lens, and I is the magnetization of the rods. Starting with the existing experimental data, we can assume that $4\pi I = 4.75$ kG. Thus, in a lens of aperture $d_a = 2$ cm and outer diameter $d_l = 9$ cm, one can obtain a magnetic field with a gradient of 5.8 kG/cm. The field gradient in a two-row lens is[74]

$$G = \sqrt{G_1^2 + G_2^2 + 2G_1G_2 \cos 2\varphi_0}.$$

Here G_1 and G_2 are respectively the gradients of the first and second rows, and φ_0 is the angle between the median axes of each row. The stability of lenses containing permanent magnets fulfills the conditions for focusing in a Linac. As direct experiments have shown, the limiting admissible integral neutron flux for maintenance of the magnetic properties of the YuNDK alloys is roughly no smaller than 10^{21} neutrons/cm^2.[78] This makes it possible to use these alloys in intense linacs. The use in the main section of the Linac of magnetically hard quadrupoles enables one to avoid heat dissipation in the volume of the drift tube and substantially increases the lifetime of the intense machine, since accidental switching off of the lenses is prevented.

The employment of sections with spatially uniform focusing in the entrance section and of magnetically hard quadrupoles in the main section allows one substantially to improve the design and electrical parameters of an intense Linac.

6. THE EFFICIENCY OF A LINEAR ACCELERATOR

The power consumed by a linear accelerator is mainly spent in the rf supply system of the accelerating resonators. The expenditures of power in the remaining technical systems of a linac are usually negligibly small in comparison with the power consumed by the rf system. The efficiency of a linear accelerator operating in a continuous regime is one of the most important parameters of the installation, since the rf supply system determines the main cost of construction and operation. The total efficiency of a linear accelerator is defined as the product of the efficiency of the rf supply system and that of the accelerating resonators. The latter quantity is equal to the ratio $P_b/(P_b + P_{Cu})$, where

$$P_b = J_b(dW_s/dz)$$

is the power per unit length that is removed by a beam of current J_b at the acceleration rate of dW_s/dz; P_{Cu} is the power per unit length of the active losses in the copper:

$$P_{Cu} = E_0^2/2R_{sh}\ .$$

Here E_0 is the mean field at the axis of the resonator, and R_{sh} is the shunt impedance per unit length of the resonator.

Since in pulsed Linacs the beam carries away a relatively small fraction of the total energy $W_e = (Q/\omega)P_{Cu}$ that is stored in the accelerating field, the efficiency of pulsed Linacs is very low. Even in the Linacs of meson factories, the efficiency does not exceed 2–4%, while in the injectors of proton synchrotrons it does not exceed fractions of one percent.

As a rule, the rf power carried away by the beam in continuous-action intense Linacs is considerably greater than the active losses in the walls of the resonators. This requires one to design rf power supply systems with a very large mean power, but it creates conditions for a substantial increase in efficiency. The accelerating resonators of proton Linacs have $R_{sh} \approx 15-20$ MΩ/m.[21] Since we have

$$\frac{dW_s}{dz} = E_0 T \cos \varphi_s,$$

then for a beam current of 300 mA and a rate of acceleration of 1 MeV/m, the efficiency of the accelerating resonators amounts to a value of the order of 85%.[43]

We can expect that the efficiency of rf generators will reach 70–80% in the very near future.[9] In this case the overall efficiency of a shortwave Linac with a continuous beam current of 100–300 mA will amount to 50–60%.

7. CONCLUSION

The past decade has been marked by substantial progress, both in the field of developing new accelerating and focusing systems for linear ion accelerators, and in understanding the theoretical problems associated with the acceleration of intense beams in these accelerators. A number of designs have been proposed for intense linear accelerators intended for solving important problems of energetics. The technical difficulties that must still be overcome in the process of further technological development are large. Yet we can already state that the building of large installations of power up to 300–500 MW with intense linear ion accelerators possessing the required parameters of energy, beam current, and efficiency is feasible.

The author thanks B. L. Ioffe for valuable discussions of the problems of employing intense accelerators.

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Translated by M. V. King